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Electroluminescence properties of a new asymmetric AlSbAs/InAs/II–VI double heterostructure grown by MBE

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Recently new physical approach and new energy band design has been proposed by us to create high-power mid-infrared lasers with improved performance [1]. It can be achieved in a laser structure with high asymmetric barriers for electrons and holes at the interfaces between a narrow-gap active layer and wide-gap cladding layers.

In this case the narrow-gap active layer sandwiched between the wide-gap layers forms type I heterojunctions with them, whereas the n- and p-confining layers form a type II heterojunction pair and have energy gap much higher than the photon emission energy (Fig. 1). In such heterostructure a strong overlap of electron and hole wave functions in the type I quantum well (QW) active layer placed at the type II heterointerface takes place. It leads to the higher optical gain and quantum efficiency as in conventional type I double heterostructure lasers, but with substantial suppression of both injection and non-radiative losses. In the proposed device a low threshold current and its weaker temperature dependence are expected. Total current is expected to be determined mostly by a radiative recombination in the active region of the laser structure.

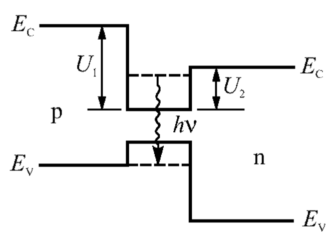

Fig. 1. Schematic band diagram of asymmetric laser heterostructure design.

There exist only three III–V compounds to design the proposed laser structures, which could provide high enough barriers for electrons and holes simultaneously: AlAsSb-InAs-InP. However, the latter is strongly lattice-mismatched to the former two, making practically impossible to grow a pseudomorphic laser structure with a strong hole confinement in the InAs active layer by any of state-of art technological methods (LPE, MBE, MOCVD).

A novel approach, which we propose in this paper, consists in combining III–V and II–VI compounds in one laser heterostructure, which allows one to achieve the necessary large valence band offset ΔE_V, keeping the whole structure pseudomorphic. A new asymmetric double heterostructure including AlAsSb/InAs (as a III–V part) and CdMgSe/CdSe (as a II–VI part), which is proposed as an active region for the modified mid-infrared laser, was grown for the first time by MBE on p$^+$-InAs (100) substrate.

The III–V part grown at a substrate temperature $T_S = 480°$C consists of a 0.1 μm thick p$^+$-InAs:Be buffer layer followed by a 20 nm thick p-AlAsSb:Si barrier and, finally, of an

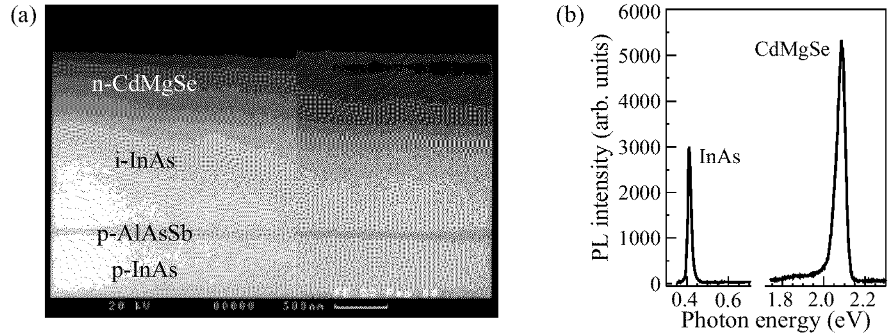

Fig. 2. Cross-sectional SEM image (a) and PL spectra at 77 K (b) of AlAsSb/InAs/CdMgSe p-i-n diode structure.

undoped 0.6 μm-InAs layer ($n < 10^{17}$ cm^{-3}). A thin As cover was used as a passivating layer to protect the surface from oxidation in atmosphere, when transferring the structure to a separate II–VI MBE chamber through the air. After removal of the As cap by annealing the wafer at $T_S < 480°$C, a Cd(Mg)Se growth was initiated with a formation of In-Cd interface by a 5 s exposure of the (4×2)In-rich InAs surface controlled by RHEED to a Cd flux. Further, a migration enhanced epitaxy (MEE) mode was employed at $T_S = 200°$C to grow $\sim$10 nm of CdMgSe nucleation layer. No 3D growth stage was observed. The rest of the II–VI structure, involving a nominally undoped 50 nm-CdMgSe layer followed by 0.3 μm of n-type CdMgSe:Cl and then by 10 nm-CdSe:Cl, was grown in MBE mode at $T_S = 280°$C under the (2×1)Se-rich conditions. $ZnCl_2$ was used as an n-dopant source. The electron concentration of $n \sim 4 \times 10^{17}$ cm^{-3} was obtained for the CdMgSe layer from C–V measurements. Mg mole fraction was estimated as 12% from x-ray diffraction (XRD) measurements which also confirm a pseudomorphic nature of the II–VI layers. The cross-sectional scanning electron microscopy image of the sample is presented in Fig. 2(a).

To measure photoluminescence (PL), we used single-grating monochromators and different excitation sources for different spectral regions. InGaAs cw laser diode emitting at 950 nm was used to excite PL in the III–V part of the structures, responsible for infra-red (IR) spectral region, while a 325 nm line of a cw He-Cd laser was used to excite PL from Cd(Mg)Se. For electroluminescence (EL) studies, the mesa-stripe samples were processed by a standard photolithography with diameters of a mesa and a contact of 300 and 50 μm, respectively. EL spectra were measured using a MDR-4 grating monochromator and a lock-in amplifier. A liquid N_2-cooled InSb photodetector was used for detection. Spontaneous EL spectra were measured both under quasi-cw conditions with pulse duration of $\tau = 2.5$ ms and filling factor of 1/2 and in a pulsed mode with a pulse duration $t = 1{-}10$ μs and a repetition rate $f = 10^3{-}10^4$ Hz.

Figure 2(b) summarizes the PL spectra measured at 77 K in the structure. Two relatively narrow peaks are visible at 0.410 eV and 2.086 eV, which are attributed to the near-band-edge radiative recombination in InAs and CdMgSe layers, respectively. To estimate the band-offset at the InAs/CdSe inerface we used the "model-solid theory" of Van de Walle [2], which suggests the type II band line-ups. InAs represents a $\sim$60 meV potential barrier for electrons at the bottom of the CdSe conduction band, whereas the heavy hole band offset at the interface is as large as $\sim$1.42 eV. An incorporation of the large enough content of Mg is expected to change the situation at the InAs/CdMgSe interface from type II to type I. Indeed, the peak energy of the CdMgSe emission band taken from the spectrum in Fig. 2(b) allows an estimation of the CdSe/CdMgSe band gap difference as about 350 meV (E_G of

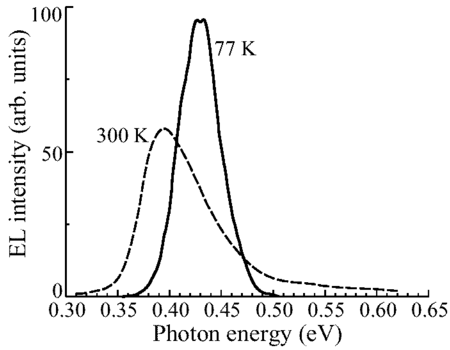

Fig. 3. EL spectra of InAs/AlAsSb/InAs/CdMgSe/CdSe laser structure at 77 K (solid line) and 300 K (dashed line).

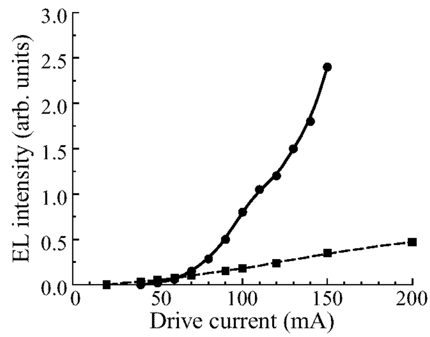

Fig. 4. EL intensity as a function of drive current at 77 K (solid line) and 300 K (dashed line).

MBE cubic CdSe has been found to be 1.74 eV at 80 K [3]). One can expect that at least a half of this value falls on the conduction band offset ΔE_C, resulting in the strong type I band alignment at the InAs/CdMgSe interface with ΔE_C at least larger than 110 meV and $\Delta E_V \sim 1.6$ eV. Thus, the AlAsSb/InAs heterointerface with well known $\Delta E_C = 1.28$ eV value and the InAs/CdMgSe heterointerface probably can prevent the electron and hole leakage from the InAs active layer.

The intense electroluminescence has been found at both 77 and 300 K as shown in Fig. 3. The EL spectrum at 77 K contains the single emission band with a photon energy maximum at $h\nu = 430$ meV and FWHM = 40 meV. The emission band had a weak asymmetric shape with abrupt high-energy edge. The room temperature EL spectrum contains also the single emission band with a photon energy maximum at $h\nu = 396$ meV and FWHM = 68 meV, although the peak has a reverse asymmetry with a noticeable short-wavelength tail. The photon energy of the spontaneous EL is close to the PL energy maximum observed in Fig. 2(b).

With the temperature increase from 77 to 300 K, the maximum EL intensity decreases just by 7–10 times, which evidences a weaker temperature dependence of the spontaneous emission in this structure compared to conventional InAsSbP/InAs-based laser structures. The dependences of EL intensity on a drive current at cw and pulsed modes were studied both at low and room temperatures (Fig. 4). The dependence of spontaneous emission at 77 K exhibits the behavior close to a superluminescence regime.

In conclusion, a new double heterostructure with high asymmetric band offsets, based on a combination of III–V (AlAsSb/InAs) and II–VI (CdMgSe/CdSe) heterostructures, has

been proposed for the first time as the active region of mid-infrared laser and successfully grown by MBE. Intense longwavelength electroluminescence has been observed both at low (77 K) and room temperature. Weak temperature dependence of spontaneous emission from the structure serves an evidence of the effective carrier confinement in the InAs layer due to high potential barriers in conduction ($\Delta E_C = 1.28$ eV) and valence ($\Delta E_V \sim 1.6$ eV) bands.

Acknowledgements

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